A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)

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LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation, primitive equation ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications. It will also benefit the ocean modeling community at large by providing the current state-of-the-art knowledge in physics, numerical schemes, and computational technology.

OBJECTIVES

The main objective is to produce a tested expert ocean-modeling framework for scientific and operational applications over a wide range of spatial (coastal to basin) and temporal (days to seasons) scales. The primary focus is to implement the most robust set of options and algorithms for relocatable coastal forecasting systems nested within basin-scale operational models for the Navy. The system is unique in that it is the only community framework that includes the adjoint-based analysis and prediction tools that are available in Numerical Weather Prediction (NWP), such as 4-dimensional variational data assimilation (4D-Var), ensemble prediction, observation sensitivity and impact, adaptive sampling, and circulation stability and sensitivity analysis. ROMS is freely distributed (http://www.myroms.org) to the Earth's modeling community and has thousands of users worldwide.

APPROACH

The structure of TOMS is based on ROMS because of its accurate and efficient numerical algorithms, tangent linear and adjoint models, variational data assimilation, modular coding and explicit parallel structure conformal to modern computer architectures (both cache-coherent shared-memory and distributed cluster technologies). Currently, both ROMS and TOMS are identical and continue improving and evolving. ROMS remains as the scientific community model while TOMS becomes the operational community model.

ROMS/TOMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and

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Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski *et al*., 2004; Warner *et al*., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom.

Several adjoint-based algorithms exist to explore the factors that limit the predictability of the circulation in regional applications for a variety of dynamical regimes (Moore *et al*., 2004, 2009). These algorithms use the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. The resulting singular vectors can be used to construct ensembles of forecasts by perturbing initial and boundary conditions (optimal perturbations) and/or surface forcing (stochastic optimals). Perturbing the system along the most unstable directions to the state-space yields information about the first (ensemble mean) and second (ensemble spread) moments of the probability density function. Given an appropriate forecast skill measure, the circulation is predictable if low spread and unpredictable if large spread.

ROMS/TOMS uniquely supports three different 4D-Var data assimilation methodologies (Moore *et al*., 2011a, b): a primal form of the incremental strong constraint 4D-Var (I4D-Var), a strong/weak constraint dual form of 4D-Var based on the Physical-space Statistical Analysis System (4D-PSAS), and a strong/weak constraint dual form of 4D-Var based on the indirect representer method (R4D-Var). In the dual formulations, the search for the best ocean circulation estimate is in the subspace spanned only by the observations, as opposed to the full space spanned by the model as in the primal formulation. Although the primal and dual formulations yield identical estimates of the ocean circulation for the same *a priori* assumptions, there are practical advantages and disadvantages to both approaches (Moore *et al.*, 2011a, b, c). To our knowledge, ROMS/TOMS is the only open-source, ocean community-modeling framework supporting all these variational data assimilation methods and other sophisticated adjoint-based algorithms.

There are several biogeochemical models available in ROMS. In order of increasing ecological complexity these include three NPZD-type models (Franks *et al.*, 1986; Powell *et al.*, 2006; Fiechter *et al.*, 2009), a nitrogen-based ecosystem model (Fennel *et al.*, 2006, 2008), a Nemuro-type lower level ecosystem model (Kishi *et al*., 2007), and a bio-optical model (Bissett *et al.*, 1999).

ROMS includes a sediment-transport model with an unlimited number of user-defined cohesive (mud) and non-cohesive (sand) sediment classes (Warner *et al.*, 2008). Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for erosion, and erodibility constant. A multi-level bed framework tracks the distribution of every size class in each layer and stores bulk properties including layer thickness, porosity, and mass, allowing the computation of bed morphology and stratigraphy. Also tracked are bed-surface properties like active-layer thickness, ripple geometry, and bed roughness. Bedload transport is calculated for mobile sediment classes in the top layer.

ROMS is a very modern and modular code written on F90/F95. It uses C-preprocessing to activate the various physical and numerical options. The parallel framework is coarse-grained with both shared-

memory (OpenMP) and distributed-memory (MPI) paradigms coexisting in the same code. Because of its construction, the parallelization of the adjoint is only available for MPI. Several coding standards have been established to facilitate model readability, maintenance, and portability. All the state model variables are dynamically allocated and passed as arguments to the computational routines via dereferenced pointer structures. All private arrays are automatic; their size is determined when the procedure is entered. This code structure facilitates computations over nested grids.

WORK COMPLETED

The major overhaul of ROMS to include nesting capabilities was completed. Due to its complexity, the nesting developing was divided in three sequential phases. **Phase I**, released as ROMS 3.5 on the 25th April 2011, included substantial modifications of the numerical kernels (NLM, TLM, RPM, and ADM) to allow a generic treatment of the spatial horizontal operators in the nesting contact regions. **Phase II**, released as ROMS 3.6 on the 23rd September 2011, included an overhaul of the lateral boundary conditions to facilitate, in a generic way, their processing or not in applications with nested grids. **Phase III**, released as ROMS 3.7 on the 18th April 2013, included the data managing and time-stepping infrastructure for one or more nesting layers.

Currently, three types of nesting capabilities are supported in ROMS: (i) *refinement* grids which provide increased resolution (3:1, 5:1, or 7:1) in a specific region; (ii) *mosaics* which connect several grids along their edges, and (iii) *composite* grids which allow overlap regions of aligned and non-aligned grids (Warner et al., 2010). The *mosaic* and *composite* grid code infrastructures are identical. The differences are geometrical and primary based on the alignment between adjacent grids. All the *mosaic* grids are exactly aligned with the adjacent grid. In general, the *mosaic* grids are special case of the *composite* grids. The nesting algorithms are flexible enough to allow complex nested grid configurations in coastal applications by permitting computations on various nested grid classes (refinement, mosaic, and composite) and nesting layers (refinement and composite grid combinations).

The 4D-Var data assimilation algorithms were updated to include: spatial convolutions on geopotential surfaces when modeling spatial error covariances, time error covariance modeling, a background quality control of the observations (Anderson and Järvinen, 1999), expected analysis and forecast errors (Moore et al., 2012), diagnostic information content (Desroziers et al., 2009), and a new Lanczos-based minimization algorithm (RBCG: Restricted B-preconditioned Conjugate Gradient) for the dual formulation (Gürol et al., 2013). The mathematical iterates and convergence rates of the RBCG algorithm are the same as the primal formulation Gauss-Newton algorithms. That is, the weak constraint (dual formulation: 4D-PSAS, R4D-Var) minimization is as affordable as the strong constraint (primal formulation: I4D-Var) minimization. This makes it practical to use 4D-PSAS and R4D-Var in operational applications.

Several new algorithms were added to the General Stability Analysis (GSA) toolkit to compute 4D-Var Hessian eigenvector analyses on the initial conditions and model forcing.

We held a very successful workshop at the Windsor Atlântica Hotel, Rio de Janeiro, Brazil, October 22-25, 2012. As in the past, several tutorials were offered on basic and advanced ROMS algorithms. In addition, we had a special session on modern observational and modeling systems with several invited speakers. We offered informal 4D-Var data assimilation workshop in Santa Cruz, CA, July 18-30, 2013. We have several attendees from US and Brazil applying 4D-Var to their own application.

RESULTS

An example of one-way nested-grids is shown in Fig. 1 for the Gulf of Mexico. Two grids are considered: a coarse grid for the full Gulf of Mexico with an average horizontal resolution of 15km (Fig. 1a) and a fine grid for the Northern Gulf of Mexico at 3km (Fig. 1b). The coarse to fine grids have a refinement ratio of 1:5. The coarse grid initial conditions and lateral boundary conditions are derived from the North West Atlantic ROMS solution. The fine grid is initialized from the coarse grid. Both grids are forced with atmospheric fields derived from the European Centre For Medium-Range Weather Forecasts (ECMWF) ERA-Interim, 3-hour dataset. River runoff is included along the Alabama, Mississippi and Louisiana coasts.

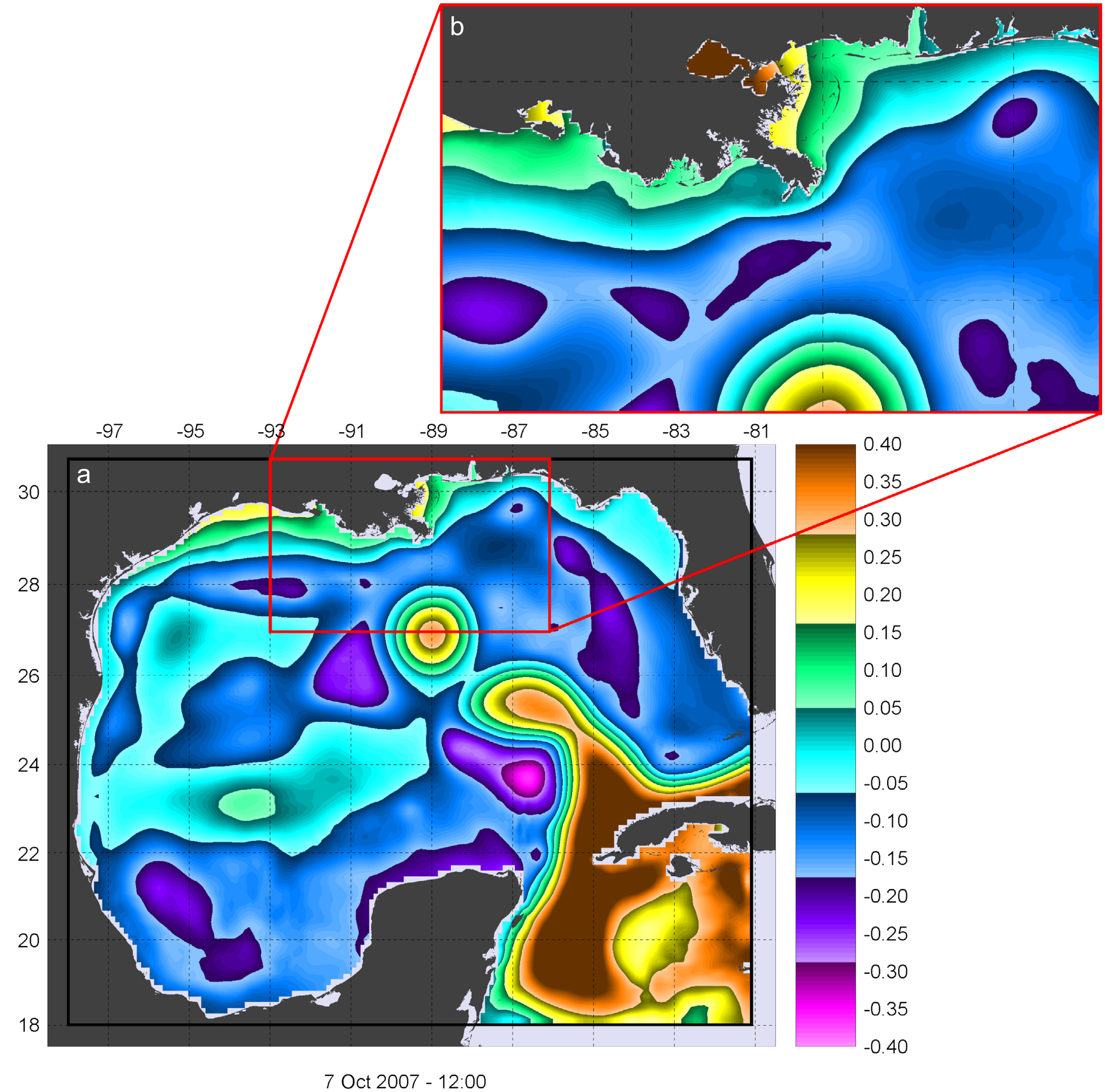

Figure 1: A ROMS nested grid application in the Gulf of Mexico showing the simulated sea surface high (m) seven days after initialization. The average horizontal resolutions are: (a) 15km for the coarser grid and (b) 3km for the fine grid. The nesting grid refinement ratio is 1:5. Notice the better-resolved features in the fine Northern Gulf of Mexico grid.

Figure 1 shows an instantaneous sea-surface height for both coarse and fine grids seven days after initialization. A well-developed Loop Current and a soon to be detached eddy can be seen. Notice that this eddy is centered on the southern lateral boundary of the fine grid.

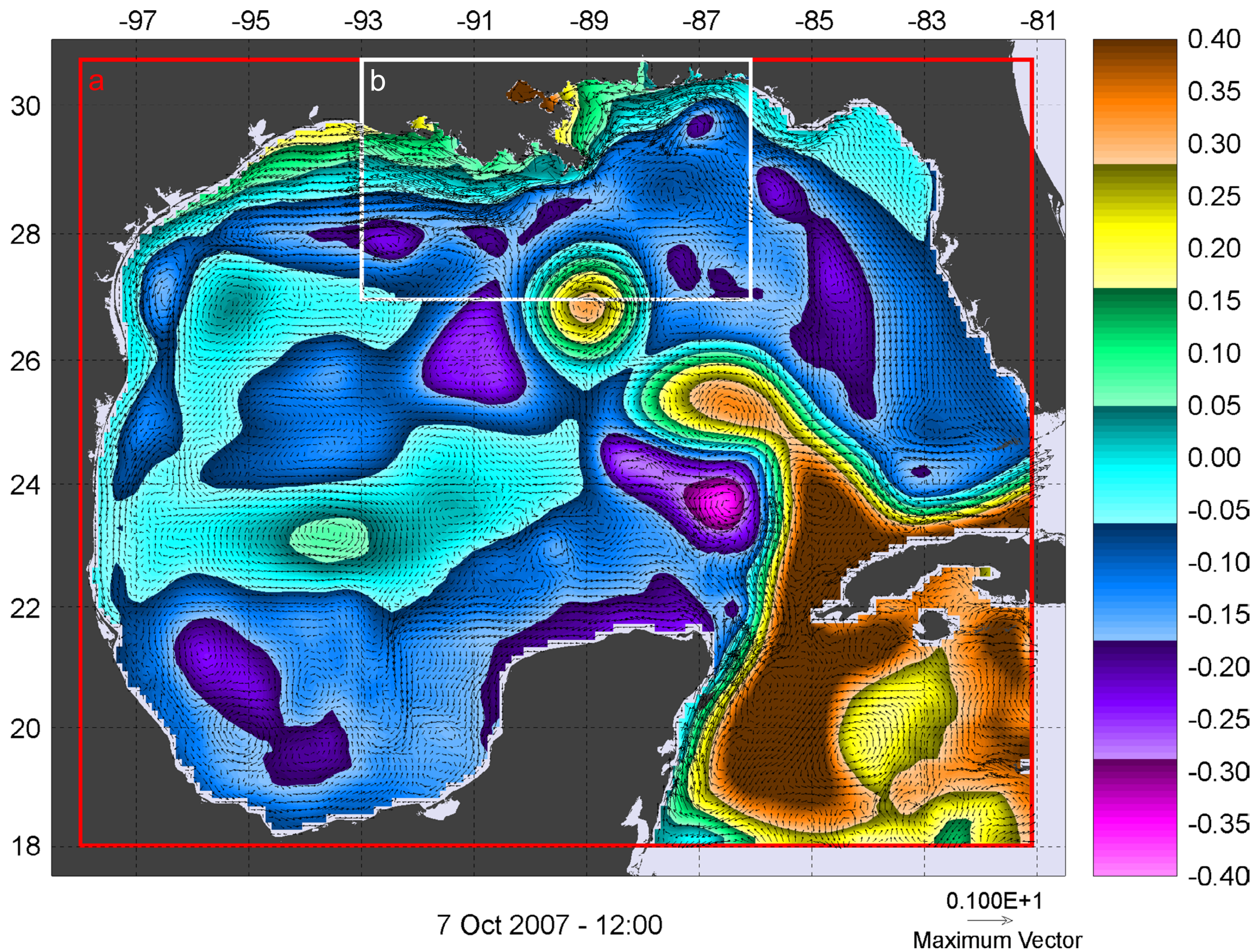

Figure 2: Sea surface high (m) and vertically integrated currents (m/s) for a one-way nesting application in the Gulf of Mexico seven days after initialization. The fine (white outline) is a 1:5 refinement ratio from coarse grid (red outline). The fine grid solution is overlaid on top of coarse grid. The fine grid current vectors have been sampled every 5 grid points for clarity.

Although this is a one-way nesting simulation, the flow of information between coarse and fine grids occurs at every time-step and the lateral boundaries are well behaved. Figure 2 shows the same fields but with the fine grid (b) on top of the coarse grid (a). In addition, the figure includes the vertically integrated currents with the fine grid vectors sampled at every fifth grid point for consistency and clarity. Notice that sea-surface height contours are continuous between both grids making the transition almost invisible without small-scale contamination. This example shows the advantages of using nesting in regional grids with very active dynamical regimes.

IMPACT/APPLICATIONS

This project will provide the ocean modeling community with a freely accessible, well documented, open-source, terrain-following, ocean model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics, stability, and sensitivity.

TRANSITIONS

The full transition of ROMS/TOMS to the operational community is likely to occur in the future. However, the ROMS/TOMS algorithms are now available to the developers and scientific and operational communities through the website http://www.myroms.org/.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (H. Arango) closely collaborates with A. Moore (adjoint-based algorithms) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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